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Two-Body Photodisintegration of the Deuteron at Forward Angles and Photon Energies Between 1.5 and 4.0 GeV

B. CONTACT PERSON:

Roy J. Holt

ADDRESS, PHONE AND BITNET:

Physics Division-203 Argonne National Laboratory, Argonne, IL 60439-4843 (312) 972-4012 Bitnet: HOLT@ANLPHY

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RESEARCH PROPOSAL

Two-Body Photodisintegration of the Deuteron at Forward Angles and Photon Energies Between 1.5 and 4.0 GeV

Submitted by

K. Coulter, S. J. Freedman, D. F. Geesamam, R. J. Holt (Spokesman),
H. E. Jackson, S. Kaufman, E. Kinney, D. Krakauer, D. Potterveld, B. Zeidman
Argonne National Laboratory, Argonne, IL 60439-4843

J. Napolitano, R. Carlini
CEBAF, Newport News, VA 23606
and
College of William and Mary, Williamsburg, VA 23185

R. Gilman
Rutgers University, Piscataway, NJ 98855

R. E. Segel
Northwestern University, Evanston, IL 60204

P. Bosted
American University, Washington, DC 20016
and
SLAC, Stanford, CA 94305

E. Beise, B. Filippone, R. D. McKeown
California Institute of Technology, Pasadena, CA 91125

R. Milner
Massachusetts Institute of Technology, Cambridge, MA 02139

D. Beck
University of Illinois, Urbana, IL 61801

Z.-E. Meziani
Stanford University, Stanford, CA 94305

R. Minehart
University of Virginia, Charlottesville, VA 22901

O. Keith Baker
Hampton University, Hampton, VA 23668

ABSTRACT

We propose in this letter to measure the energy dependence of the cross section for the $\gamma d \rightarrow pn$ reaction throughout the photon energy range 1.5 to 4.0 GeV and that for the $\gamma d \rightarrow \pi^0 d$ reaction in the range 1.5 to 3.0 GeV. This proposed experiment represents the natural extension of work that members of the above collaboration began at SLAC, where it was discovered that the energy dependence of the cross section between 1.4 and 1.8 GeV is consistent with that expected from the constituent counting rules. The purpose of the present work is to extend the SLAC measurements up to the highest energy feasible in order to determine whether or not the simple energy dependence persists throughout a larger energy range.

I. INTRODUCTION

Presently, an important issue in nuclear physics is whether or not there exist nuclear processes which require the explicit inclusion of quark-gluon degrees of freedom in the reaction dynamics in order to be understood. A guiding principle in this search is to perform experiments with high energy electromagnetic probes of the simplest nucleus, the deuteron, a system which is particularly amenable to theoretical interpretation. It has long been recognized that the constituent counting rules[1] seem to apply for electron elastic scattering[2] from the pion and nucleon, but unfortunately, this dimensional scaling region has not been reached for electron-deuteron elastic scattering because of the very small cross section at high momentum transfer. (This point has been clarified further by the observation[3] of a minimum in $B(Q^2)$ near $Q^2 = 2\ (\mathrm{GeV}/c)^2$.) This led Brodsky and Chertok[4] to analyze the electron-deuteron elastic scattering data in terms of reduced nuclear amplitudes and produce, in effect, scaling at a lower momentum transfer. Since this latter analysis has met with substantial controversy, we circumvent this difficulty by abandoning elastic electron scattering in favor of an exclusive photoreaction with the deuteron. The primary advantage is that a higher value of momentum transfer to the constituents can be achieved[5] in the $\gamma d \rightarrow pn$ reaction than in the e-d elastic scattering process (see Appendix A). The results from experiment NE8 at SLAC indicate that the $^2H(\gamma,p)n$ reaction cross sections are consistent with the constituent counting rules at the highest energy of the measurements (see Appendix B). The key issue is whether or not asymptotic scaling has been achieved as suggested by the results of NE8. It is essential to extend these measurements to the highest energy practicable in order to determine whether or not this trend continues.

The constituent counting rules for a two-body reaction process, A+B→C+D, can be summarized by the dependence of the cross section $d\sigma/dt$ on the Mandelstam variable s:

$$\frac{d\sigma}{dt} \sim s^{-n+2}$$

where $n=n_A+n_B+n_C+n_D$ is the total number of fundamental constituents involved in the reaction. A good example[6] of the success of these counting rules for a photoreaction is given by the $\gamma p \to \pi^+ n$ reaction. Here, counting the quarks in the initial and final states and the photon, n is 9, and the cross section is expected to have an s^{-7} dependence. This behavior has been observed as illustrated in Fig. 1.

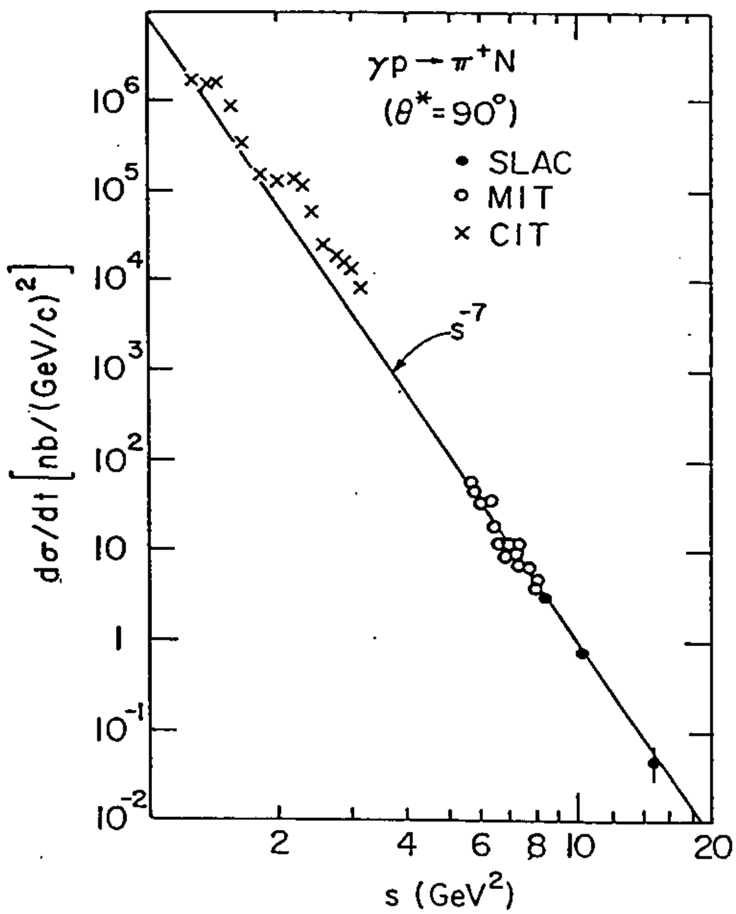

Figure 1
Cross section for the $\gamma p \to n\pi^+$ reaction. The data are consistent with the s^{-7} dependence expected from the quark counting rules above $s=5$ GeV^2.

The simplest process involving a nucleus is the $\gamma d \rightarrow pn$ reaction. Here, n=13 and an s^{-11} energy dependence is expected where the constituent counting rules are valid. As a test of the energy dependence for the $\gamma d \rightarrow pn$ reaction, an experiment (NE8) was performed at SLAC by members of the present collaboration and new data were published[7] between 0.8 and 1.6 GeV at $\theta_{cm}=90°$. Indeed, the results at the highest energy were found to be consistent with the s^{-11} dependence as illustrated by the dashed line in the upper panel of Fig. 2. Here, the data are plotted in the form of $s^{11} d\sigma/dt$ as a function of E_γ and the new SLAC results are given by the solid circles. Previous work was taken from Ref. 8 and the solid curve is the result of a meson-exchange calculation.[9] Clearly, much more work is necessary in order for this simple reaction to be described by the meson-exchange theory. During experiment NE8, data were also taken between 0.8 and 1.8 GeV at 114° and between 0.8 and 1.6 GeV at 143°. The analysis of the data at 114° is nearly complete and the results also indicate an s^{-11} dependence above 1.4 GeV. The data at 143° are more difficult to analyze owing to a large two-step background and a Monte Carlo simulation of the background is in progress in order to assist with the analysis.

The results of a reduced amplitude analysis are shown in the lower panel of Fig. 2. According to Brodsky and Hiller,[10] the reduced amplitude $f(\theta_{cm})$ should be independent of energy where this analysis is valid. Although the discrepancy with this analysis is largest at the highest energy where the s^{-11} description seems to work the best, the data are also consistent with the reduced amplitude analysis. Thus, data at higher energy are essential in order to (i) determine whether or not the s^{-11} energy dependence persists and (ii) as an additional test of the reduced nuclear amplitude approach.

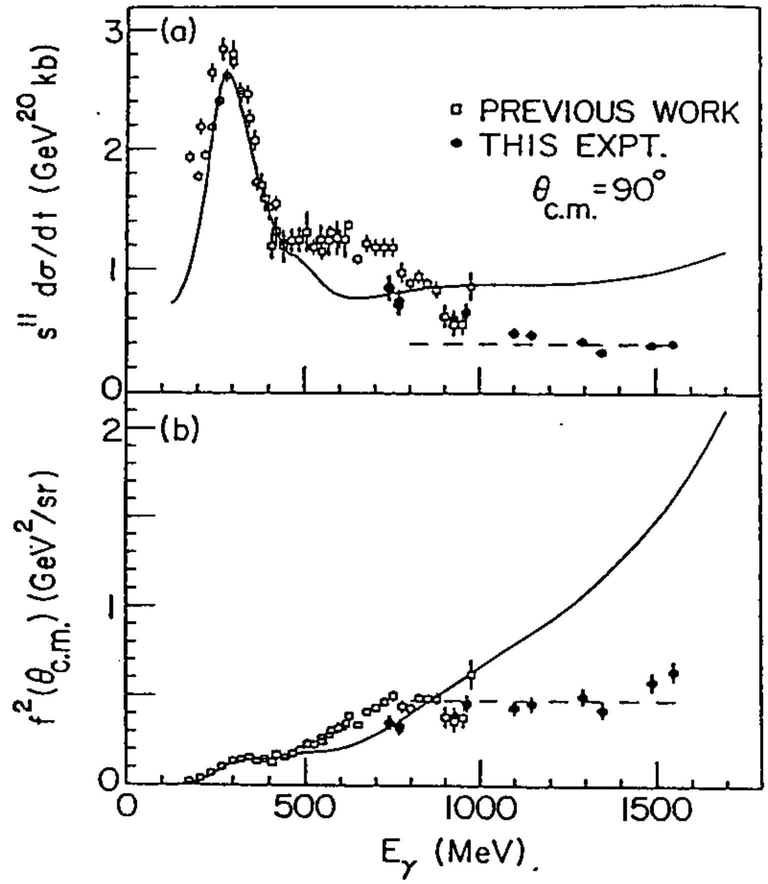

Figure 2
The upper panel is $s^{11}d\sigma/dt$ as a function of E_γ. The solid curve represents the meson-exchange calculation of Ref. 9, while the dashed line represents a constant energy dependence. Clearly, the results for $E_\gamma \gtrsim 1.2$ GeV are consistent with an s^{-11} energy dependence. The reduced nuclear amplitude for the $\gamma d \to pn$ process is shown in the lower panel. Again, the solid curve represents the meson-exchange calculation and the dashed line would represent a constant energy dependence of $f^2(\theta_{cm})$ as expected from Ref. 10. Note that the dashed lines are not results of normalized calculations, but only an indication that the cross section scales.

It is believed[11] that on the basis of a one-graph meson-exchange model of the $\gamma d \to pn$ process that at high energy the cross section will have the same energy dependence as that expected from the constituent counting rules. This argument is plausible under the assumptions and has motivated T.-S. H. Lee to extend his calculations to higher energy as a first step in understanding the energy dependence. This calculation is illustrated as the solid curve in Fig. 3. The dashed and dotted curves illustrate the energy dependence of the constituent counting rules and reduced amplitude analysis, respectively, and with the assumption that asymptotic scaling begins at 1.4 GeV, where the curves are normalized to the NE8 data. The results in Fig. 3 illustrate the importance of determining the energy dependence of this fundamental nuclear reaction process at high energies and the need for better understanding of the meson-exchange model at high energy.

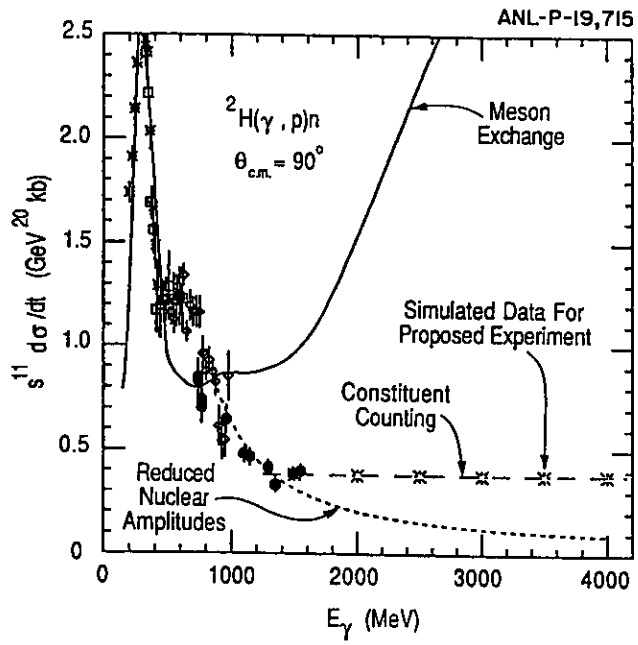

Figure 3
The energy dependence of the quantity $s^{11}d\sigma/dt$. The solid curve represents an extension of the meson-exchange calculation of Ref. 9, while the dotted curve represents the reduced nuclear amplitude analysis of Ref. 10. The dashed curve indicates the energy dependence expected for asymptotic scaling. The dashed and dotted curves are arbitrarily normalized to NE8 data near 1.4 GeV. The data at 90° from NE8 (Ref. 7) are shown as the solid points. The other data are from Ref. 8. The asterisks along the constituent counting curve indicate the energies and error limits of the proposed measurements.

A second fundamental exclusive process involving a photon and deuteron in the initial state is the $\gamma d \to d\pi^0$ reaction. Here, according to the constituent counting rules, the cross section at a fixed center-of-mass angle should have an s^{-13} dependence in the asymptotic scaling region.

Unfortunately, no data for this reaction have been published[12] above 1 GeV. This reaction may be the only remaining practical case in nuclei for tests of the constituent counting rules, since processes involving other nuclei would have a cross section decreasing more rapidly with increasing energy.

The key issue is whether or not asymptotic scaling has been achieved as suggested by the results of SLAC experiment NE8. It is essential to extend these measurements to the highest energy practicable in order to determine whether or not this trend continues. It appears feasible to extend the data for the $D(\gamma,p)n$ reaction to a photon energy of 4.0 GeV (s=18.5 GeV^2) at CEBAF by using the High Momentum Spectrometer (HMS) in order to detect the proton. It also appears feasible to extend the $\gamma d \to d\pi^0$ measurements from 1 GeV to 3.0 GeV with the same technique and with minimal impact on the beam time request. The use of the HMS also renders measurements of the $D(\gamma,p)n$ reaction feasible at forward angles, so that the angular distributions begun in SLAC experiment NE8 could be completed. Another point of interest is that the meson-exchange model and the QCD arguments disagree even more at forward angles than at backward angles. The most forward angle achievable with the HMS spectrometer corresponds to 30° in the center-of-mass. Specifically, we propose to measure the differential cross section for $\gamma d \to pn$ at θ_{cm}=30°, 53° and 90° for E_γ=1.5 to 4.0 GeV. The backward angles will be avoided in this experiment owing to a large two-step background expected at high energy and large angles. In addition, we propose to measure the cross section for the $\gamma d \to d\pi^0$ at θ_{cm}=45° and 90° for E_γ=1.0 to 3.0 GeV.

II. PROPOSED EXPERIMENTAL PROCEDURE

The proposed method makes use of bremsstrahlung photons produced from the CEBAF electron beam. The bremsstrahlung photons would irradiate a deuterium target, and photoprotons from the $D(\gamma,p)n$ reaction would be detected in the HMS spectrometer. A schematic diagram of the proposed experiment arrangement is shown in Fig. 4. A radiator (r.ℓ.=6%) would be located only 1-m upstream of the LD_2 target in order to eliminate photon losses due to multiple scattering of electrons in the radiator and the divergence of the electron beam. The requirements on the electron beam characteristics are a spot-size radius of 1.5 mm and a half-angle divergence of 2.0 mr. In order to eliminate protons produced by electrodisintegration of the target nuclei, a difference between radiator in and out will be measured. The geometry is essentially that of experiment NE8 at SLAC except that the HMS spectrometer is used instead of the 1.6-GeV spectrometer. The expected counting rates are practicable and they are summarized in Table 1 for the following conditions: (i) I_e=30 μA, (ii) $\Delta\Omega_p$=6.4 msr, (iii) liquid deuterium target thickness equals 10 cm, (iv) $d\sigma/dt$ at θ_p^{cm}=90° follows an energy dependence given by s^{-11} and is normalized to the SLAC NE8 data at E_γ=1.3 GeV. The expected counting rates at 90° then range from 230 min^{-1} at 1.5 GeV to 1.0 min^{-1} at 4.0 GeV. The expected rates for the $\gamma d \to \pi^0 d$ reaction are given in Table 2.

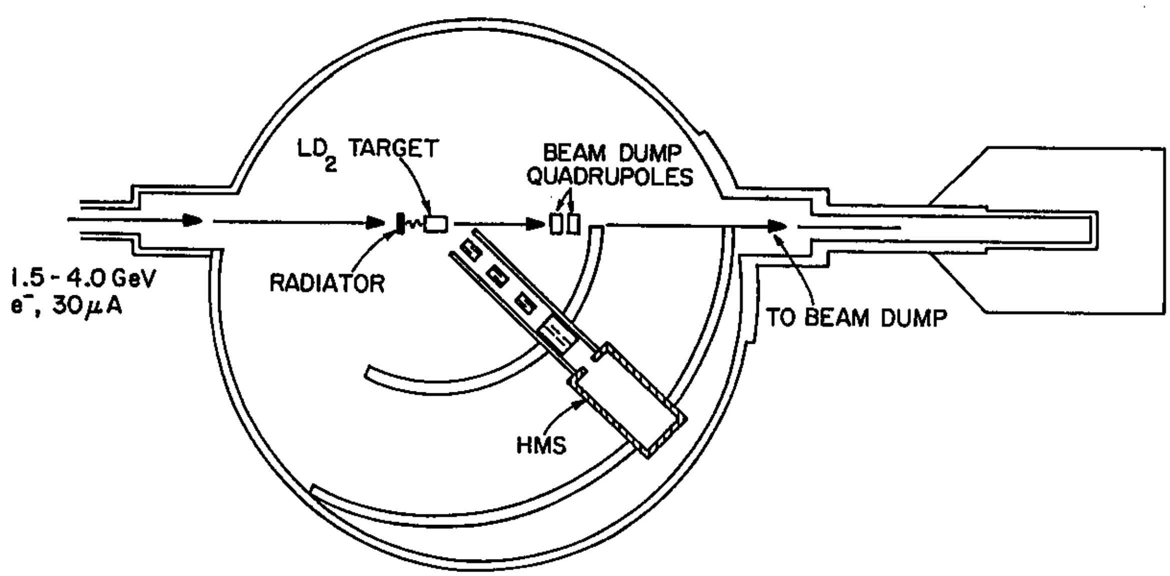

Figure 4
Proposed experimental setup to measure the cross section for the $D(\gamma,p)n$ and $D(\gamma,d)\pi^0$ reactions.

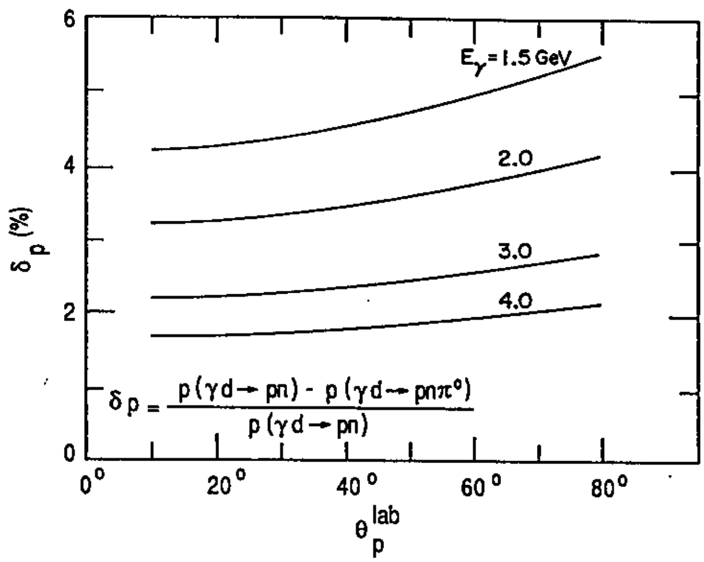

Figure 5
The momentum difference of the protons emitted from the $D(\gamma,p)n$ and $D(\gamma,p)n\pi^0$ reactions, where the relative energy between the n and π^0 is zero, as a function of θ_p^{lab}. The difference is shown for four incident photon energies spanning the range of interest here.

An essential element of the experiment is to ensure that the detected protons do not come from other processes, e.g. $D(\gamma,p)n\pi^0$, $D(\gamma,p)p\pi^-$, $D(\gamma,p)n\pi^0\pi^0$, $D(\gamma,p)n\pi^+\pi^-$, $D(\gamma,p)p\pi^-\pi^0$ or even $H(\gamma,p)\pi^0$. The proposed method of eliminating the inelastic reactions is simply to note that for a given photon energy and reaction angle, protons in which pions appear in the final state will be lower in momentum than those from the $D(\gamma,p)n$ reaction. Thus, the energy resolution of the spectrometer must be sufficient to separate protons arising from the inelastic processes. The worst case to consider is the $D(\gamma,p)n\pi^0$ reaction in which the relative energy of the n and π^0 is zero. The difference in momenta between the protons from the primary reaction and this worst-case condition is illustrated in Fig. 5. The best resolution is necessary at high-photon energies and large reaction angles. Clearly, a momentum resolution of ±0.15% should be sufficient to separate the inelastic processes. More importantly, this spectrometer resolution is necessary to identify the bremsstrahlung endpoint and the spectral shape so that the correct photon flux is applied to the data analysis. A photon tagging method would lessen to some extent the requirement on the spectrometer resolution, but the rate would be much lower and even with a large solid angle detector the experiment would be significantly more difficult if not impossible at the high energies.

Other positively-charged particles, such as π^+ or e^+ will be discriminated by dE/dx, time-of-flight, and a heavy-gas Cerenkov counter in the detector stack. Furthermore, pions from the $H(\gamma,\pi^+)n$ or $^2H(\gamma,\pi^+)nn$ reactions will not be accepted by the spectrometer for the kinematic range proposed here, and thus, π^+ contamination could arise only from multiple processes with a very restrictive phase space or from the $A\ell$ windows of the target cell. It is estimated that in the worst case, E_γ=4.0 GeV, that the π^+/p ratio will be 10:1 and the e^+/p ratio will be negligible. This contamination can be eliminated by a time-of-flight system for lower momenta and a heavy-gas Cerenkov counter at the highest momenta. Based upon our experience with NE8, a 300 ps time resolution should be practical.

A possible proton detector stack for the HMS is shown in Fig. 6. The time-of-flight between S1, S2 and S3 would provide a check on the separation of protons from the background events.

For the case of the $D(\gamma,d)\pi^0$ reaction, the time-of-flight system will be more than adequate for eliminating p and π^+ from the photodeuterons. Even though protons from the $D(\gamma,p)n$ reaction would be kinematically accepted by the spectrometer during the $D(\gamma,d)\pi^0$ experiment, the ratio of p/d is expected to be $\lesssim$100 in the worst case and the deuterons are easily isolated by time-of-flight and dE/dx. Although recoil deuterons from electron and Compton scattering are not resolvable in this experiment, their yield is estimated to be negligible at this momentum transfer.

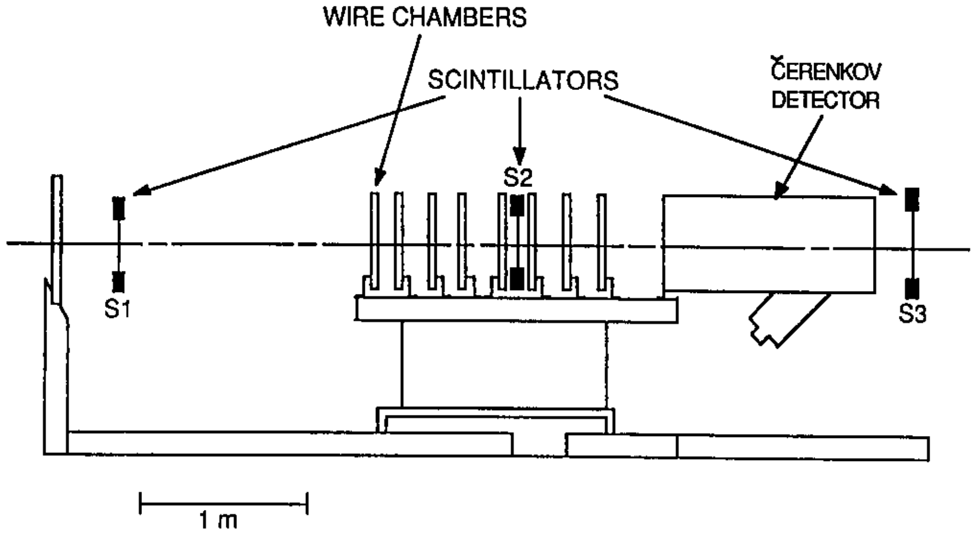

Figure 6
The proposed HMS hadron detection system. Particles will enter from the left. Time-of-flight between the scintillators will be used for particle identification. Wire chambers will be used to find the trajectories of the scattered particles and hence allow their kinematic reconstruction. A heavy-gas Cerenkov detector may be necessary for additional pion rejection.

As in SLAC experiment NE8, the photon beam flux normalization will be determined from the calculations of Matthews and Owens[13] and by measuring the electron current and radiator thickness. The effect of electrodis-integration of the deuteron in the target will be subtracted by repeating the experiment without the radiator. The virtual photon yield will be approximately that of a radiator with a radiation length of 1.5%. The spectrometer solid angle will be checked by comparing with the well-known e-p elastic scattering results and previous measurements of the D(γ,p)n experiment at the lower photon energy.

We propose to measure the cross section at θ_{cm}= 30°, 53° and 90° for E_γ=1.5 to 4.0 GeV in 0.5 GeV steps. In addition, we propose to measure the cross section for the $\gamma d \to d\pi^0$ reaction at θ_{cm}=45° and 90° for E_γ=1.0 to 3.0 GeV. In arriving at time estimates for the measurement, we assumed counting rates determined in the same manner as those shown in Tables 1 and

2. It was assumed that data would be taken at 1.5 GeV and θ_{cm}=90° in order to overlap the previous measurement and provide a high data rate for final tune-up of the experiment. In terms of time necessary for angle, energy and target changes, the following assumptions were made: (i) angle, target and radiator changes require 10 minutes each, (ii) an energy change requires ~4 hours, and (iii) the statistical accuracy required is 10% for the final answer. These conditions and time estimates are consistent with the actual NE8 experiment. Thus, we are requesting 253 hours of beam time, as indicated in Table 3.

TABLE 1
Expected count rate for D(γ,p) reaction at θ_{cm}=90°
and several photon energies

E_γ (GeV)	$d\sigma/d\Omega^{lab}$ (nb/sr)	I_p (min^{-1})
1.5	11.6	1284
3.0	0.17	8.6
4.0	0.02	1.0

Assumptions: I_e=30 μA, $\Delta\Omega_p$=6.4 msr, t_D=1.7 g/cm^2, r.ℓ.=6%.

TABLE 2
Expected count rate for the D(γ,d)π^0 reaction at θ_{cm}=90°
based on s^{-13} scaling.

E_γ (GeV)	$\frac{d\sigma}{d\Omega}^{lab}$ (nb/sr)	I_d (min^{-1})
1.5	3.7	410
2.0	0.50	37
2.5	0.09	7.0
3.0	0.02	1.2

TABLE 3
Estimated* time for experiment.

Data Acquisition $D(\gamma,p)n$	69 hours
$D(\gamma,d)\pi^0$	50 hours
Calibration Runs	24 hours
Overhead	50 hours
Spectrometer and Detector tune-up	60 hours
	253 hours

*Accelerator is assumed to operate at 30 μA current and with 100% reliability.

III. EXPERIMENTAL EQUIPMENT

The proposed experiment is compatible with the 6-GeV spectrometer being discussed for Hall C. Specifically, the requirement for this experiment is a spectrometer of maximum momentum 4.4 GeV/c, resolution ±0.15%, $\delta p/p=\pm5\%$, $d\Omega=6.4$ msr and target length acceptance ≃ 10 cm.

Beyond the usual detector stack for a spectrometer, a time-of-flight system and a gas Cerenkov counter filled with isobutane or an equivalent gas would be necessary for particle identification. As with the SLAC spectrometers approximately 4 meters is required in the detector hut for the time-of-flight system. High-power (~150 w) liquid deuterium and hydrogen targets and a remotely changeable radiator assembly are necessary. Although CEBAF has the responsibility for providing the cryogenic target, it may be possible to use a modified version of the proposed Caltech target which is being designed for use at MIT-Bates.

IV. COLLABORATION

Members of this collaboration have submitted a proposal to NPAS in order to carry out this experiment up to $E_\gamma=3$ GeV. If this experiment at NPAS should be approved and run, we would argue that it is essential to extend the $D(\gamma,p)n$ measurement to even higher energy. Based on count rate, the highest feasible energy is expected to be 4 GeV at CEBAF.

The collaboration is a strong, viable group with much experience in performing experiments at SLAC in the GeV region. Members of the group have been strongly involved in the Nuclear Physics at SLAC program. In fact, the group, named here, successfully performed the first measurements of the $\gamma d \rightarrow pn$ reaction (experiment NE8 at SLAC) above 1 GeV (see Appendix B). For the SLAC experiment, this collaboration provided the complete detector system for the spectrometer, electronics and data acquisition software. Approximately half of the Medium Energy Physics manpower and resources at Argonne were required for approximately two years in order to mount the experiments NE1 and NE8 at SLAC. Similar commitments have been made by other institutions named in this proposal. Clearly, a substantial commitment of this kind would be expected for the present proposed experiment at CEBAF.

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Exclusive photonuclear reactions and asymptotic scaling

R. J. Holt

Physics Division, Argonne National Laboratory, Argonne, IL 60439-4843

(Received

ABSTRACT

Recent measurements of electron-deuteron elastic scattering at high momentum transfer have placed an empirical lower limit on the momentum transfer for the onset of asymptotic scaling. The implications that this limit has for the $^2H(\gamma,p)n$, $^2H(\gamma,d)\pi^0$ and $^3He(\gamma,d)H$ reactions will be discussed.

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It is widely believed that asymptotic scaling in hadronic reactions occurs when the reaction cross sections obey the power law dependence of the constituent counting rules.[1] With this operational definition, asymptotic scaling appears to occur in high energy proton-proton elastic scattering[2] and photo-pion production[3] from the proton. In addition, electron elastic scattering cross sections for the nucleons[4] and that deduced for the pion at high momentum transfer appear to obey the constituent counting rules. Although there is some debate[5] about the validity of perturbative QCD in these cases, there is a consensus that QCD is essential to explain these simplest hadronic reactions. However, for nuclear reactions, the meson exchange model has met with considerable success and since it is unlikely that the quarks in a nucleus are deconfined from the hadrons, it is not widely believed that QCD is necessary to describe nuclear reactions or that asymptotic scaling should be observed.

Indeed, the most intensively studied nuclear process, electron-deuteron elastic scattering, indicates that the cross section[6,7] at the highest momentum transfer does not scale. The cross section $\sigma(Q^2)=\sigma_M[A(Q^2)+B(Q^2)\tan^2(Q/2)]$ can be described by two components $A(Q^2)$ which depends primarily upon the electric form factors of the deuteron and $B(Q^2)$ which depends only on the magnetic form factor. The lack of asymptotic scaling at presently attainable values of momentum transfer, Q, is illustrated in the upper panel of Fig. 1. Since one would expect the cross section to fall off as $\sigma/\sigma_M \sim 1/Q^{20}$ according to the constituent counting rules, then the quantity $(\sigma/\sigma_M)Q^{20}$ should approach a constant value in the scaling region. Clearly, this could only occur at $Q^2>4$ $(GeV/c)^2$. This argument is strengthened by noting that the recent measurements[7] of $B(Q^2)$, shown in the lower panel of Fig. 1, exhibit a minimum near $Q^2=2$ $(GeV/c)^2$.

The presence of this minimum in the form factor is characteristic of a two-nucleon description of the deuteron. Furthermore, the curves shown in Fig. 1 are in good agreement with these data and represent a calculation[8] based only on the two-nucleon model of the deuteron. Thus, it seems evident that one should not expect asymptotic scaling to occur in e-d elastic scattering for $Q^2<4\ (\mathrm{GeV}/c)^2$.

In order to understand the implications that this result has for the $\gamma d \to pn$ reaction, it is important to set a lower limit on the momentum transfer to the constituents in the deuteron. Although it is important ultimately to consider the momentum transferred to the individual quarks in the nucleus, it is convenient to consider only the momentum transferred to the nucleons. For electron-deuteron elastic scattering, consider the schematic diagram illustrated in Fig. 2a. The square of the average momentum transferred t_N to a nucleon in the deuteron is given by

$$t_N^{ed} = (P_d'/2 - P_d/2)^2$$

which reduces to

$$t_N^{ed} = - m_d T_d/2 = - (Q/2)^2$$

where $Q=P_e'-P_e$ is the usual four-momentum transfer for electron scattering and T_d is the kinetic energy of the scattered deuteron. In a similar fashion, the momentum transferred to a nucleon in the $\gamma d \to pn$ reaction can be determined by considering the diagram in Fig. 2b. Here, the square of the momentum transferred to a nucleon is given by

$$t_N^{\gamma d} = (P_N - P_d/2)^2$$

where P_N is the four-momentum of the recoil nucleon and P_d is the initial four-momentum of the deuteron. This reduces to

$$t_N^{\gamma d} = m_N^2 + (m_d/2)^2 - m_d\ E_N \tag{1}$$

where E_N is the total energy of the nucleon. With the approximation that $m_d \approx 2m_N$, then

$$t_N^{\gamma d} \approx -\ 2\ m_N T_N$$

where T_N is the laboratory kinetic energy of the recoil nucleon. Perhaps the most surprising result from this analysis is the relatively large amount of momentum transferred to a nucleon in the deuteron photodisintegration process for relatively low incident photon energy compared with that from elastic electron scattering. This is illustrated in Fig. 3, where $t_N^{\gamma d}$ is given as a function of photon energy E_γ for the $\gamma d \rightarrow pn$ reaction at $\theta_{cm}=90°$. For comparison, the Q^2 in e-d scattering which gives the same t_N is shown on the right vertical axis. The dashed line illustrates the empirical lower limit of $Q^2=4$ $(GeV/c)^2$ or $t_N=-1$ $(GeV/c)^2$ for the onset of asymptotic scaling. This gives a lower limit of only $E_\gamma=1.1$ GeV for the incident photon energy, i.e. the available elastic electron scattering data do not give scaling information for the $\gamma d \rightarrow pn$ reaction above a photon energy of 1.1 GeV.

Recent data[9] from SLAC extend up to $E_\gamma=1.6$ GeV for the deuteron photodisintegration at $\theta_{cm}=90°$, giving $|t_N|=1.5$ $(GeV/c)^2$, and there is evidence for scaling above 1.4 GeV. An electron scattering experiment which would give comparable momentum transfer to the nucleons would have to be performed at $Q^2=6$ $(GeV/c)^2$. It is believed[10] that data for the $\gamma d \rightarrow pn$ reaction can be extended up to $E_\gamma=3$ GeV at SLAC and 4 GeV at CEBAF. This latter value would give $t_N=-3.8$ $(GeV/c)^2$ and a comparable electron scattering experiment would have to be performed at $Q^2=15$ $(GeV/c)^2$. Clearly, the $\gamma d \rightarrow pn$ reaction is a powerful method for the study of asymptotic scaling in nuclei.

It is interesting to apply a similar analysis to binary photoreactions involving a nucleus in the initial and final states. The simplest binary reactions with the least power law fall off in the asymptotic region are $\gamma d \to \pi^0 d$ and $\gamma {}^3He \to pd$. Here, it is sufficient to calculate the momentum transfer t_d to the deuteron and compare this with that in electron-deuteron elastic scattering. For the case of $\gamma d \to \pi^0 d$, the momentum transfer is given by

$$t_d = - 2m_d T_d$$

where T_d is the outgoing kinetic energy of the deuteron. The momentum transfer t_d is given as the solid curves in Fig. 4 for $\theta_{cm}=45°$ and 90°.

The momentum transfer to the deuteron, t_d, for the ${}^3He(\gamma,d)p$ reaction is represented by the dashed curves in Fig. 4 for comparison to that of the ${}^2H(\gamma,d)\pi^0$ reaction. Of course, more momentum is imparted to the deuteron at a more forward reaction angle. For example, at $\theta_{cm}=45°$ a momentum transfer of $t_d=-4$ $(GeV/c)^2$ to the deuteron can be achieved with the absorption of only a 1.6-GeV photon. Proposals[10,12] at both SLAC and CEBAF exist to study these reactions in the GeV region.

In summary, it appears that photoreactions in few-body systems are an extremely promising method to search for the onset of asymptotic scaling in exclusive nuclear reactions. The main problem in previous electron scattering studies is that it is necessary to impart more than $Q^2=4$ $(GeV/c)^2$ to the deuteron and this has proved impractical owing to the extremely small cross section. However, for the ${}^2H(\gamma,p)n$ reaction this momentum transfer to the constituents has already been exceeded[9] experimentally and it appears practical to extend the momentum transfer to the constituent nucleons to greater than 2.5 $(GeV/c)^2$ at SLAC and greater than 3.8 $(GeV/c)^2$ at CEBAF. In order to compete with this latter momentum transfer, a corresponding elastic scattering experiment would have to be performed at $Q^2 \approx 15\ (GeV/c)^2$! With regard to momentum transfer to the deuteron itself, it may be possible to exceed the present limit from electron scattering by performing experiments[10,12] with the reactions $^2H(\gamma,d)\pi^0$ or $^3He(\gamma,d)H$. Unfortunately, there are no cross section data available in the GeV region to determine the practicability of these experiments. However, it is likely that these experiments could be performed for a photon energy as high as 2 GeV at CEBAF, and thus photo-deuteron reactions could be studied at a higher momentum transfer to the deuteron than hitherto possible in electron-deuteron elastic scattering.

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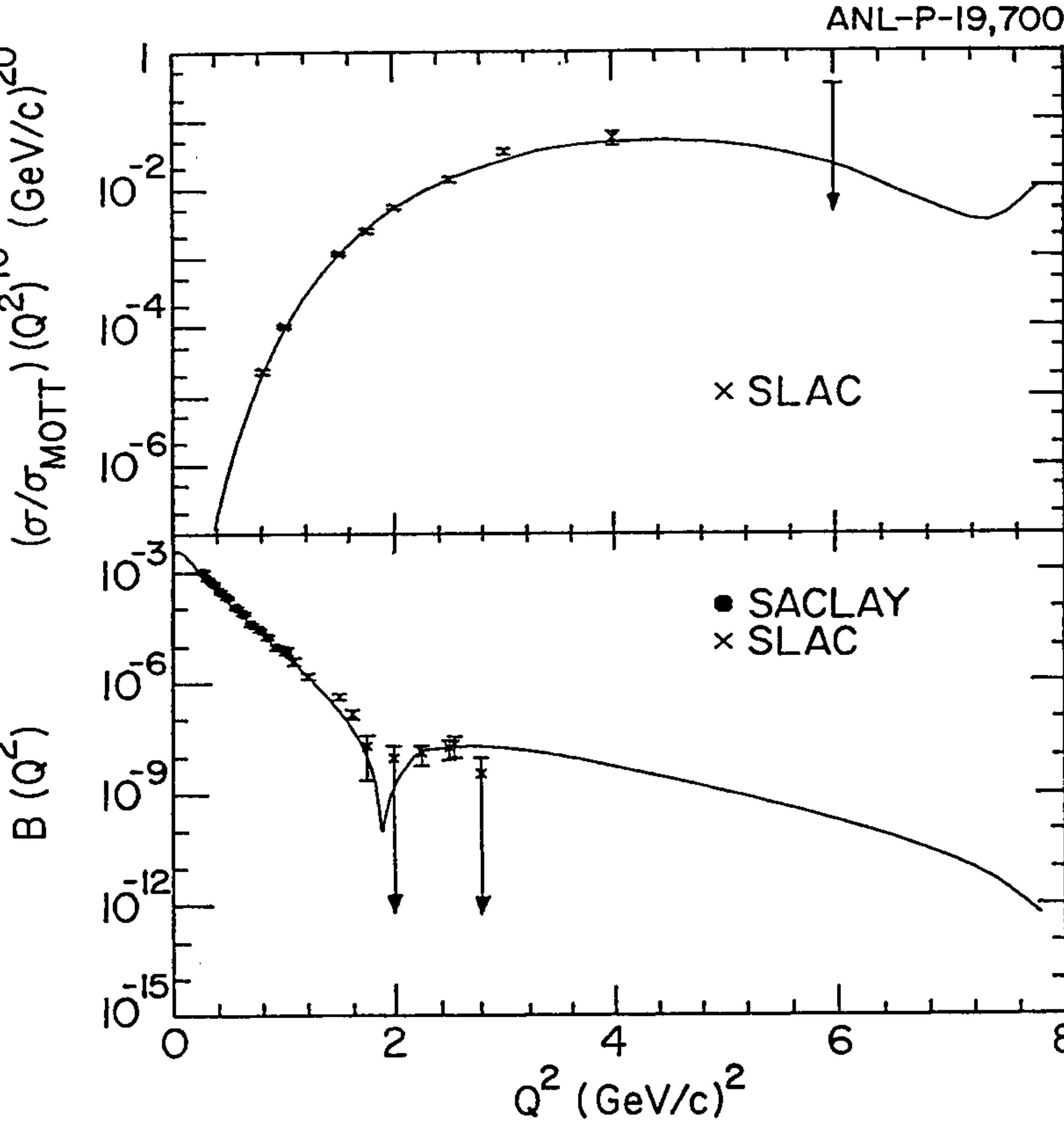
FIGURE CAPTIONS

Fig. 1 Electron-deuteron elastic scattering. The data points in the upper panel are from Ref. 6, while those in the lower panel are from Ref. 7. The theoretical curves are from Ref. 8. There is no evidence for asymptotic scaling for $|Q^2|<4$ $(\mathrm{GeV}/c)^2$.

Fig. 2 Illustrations of momentum transfer to the nucleons in (a) electron-deuteron elastic scattering, and (b) photodisintegration of the deuteron.

Fig. 3 The square of the four-momentum transfer to a nucleon in the $^2\mathrm{H}(\gamma,p)n$ reaction at $\theta_{cm}=90°$ as a function of incident photon energy. The right vertical axis indicates the momentum transfer to a deuteron in electron-deuteron elastic scattering to yield the same momentum transfer to a nucleon as that in the $^2\mathrm{H}(\gamma,p)n$ reaction. The dashed line indicates the $Q^2=4$ $(\mathrm{GeV}/c)^2$ point in electron-deuteron elastic scattering and is the equivalent in momentum transfer to the constituents as absorption of a 1.1 GeV photon in the $^2\mathrm{H}(\gamma,p)n$ process at $\theta_{cm}=90°$.

Fig. 4 The square of the four-momentum transfer to a photo-deuteron in the $^3\mathrm{He}(\gamma,d)\mathrm{H}$ reaction (upper two curves) and the $^2\mathrm{H}(\gamma,d)\pi^0$ reaction (solid curve) as a function of photon energy.



ANL-P-19,700
$(\sigma/\sigma_{MOTT})(Q^2)^{10}$ (GeV/c)^{20}
1
10^{-2}
10^{-4}
10^{-6}
× SLAC
$B(Q^2)$
10^{-3}
10^{-6}
10^{-9}
10^{-12}
10^{-15}
● SACLAY
× SLAC
0
2
4
6
8
Q^2 (GeV/c)^2

Fig. 1

ANL-P-19,698

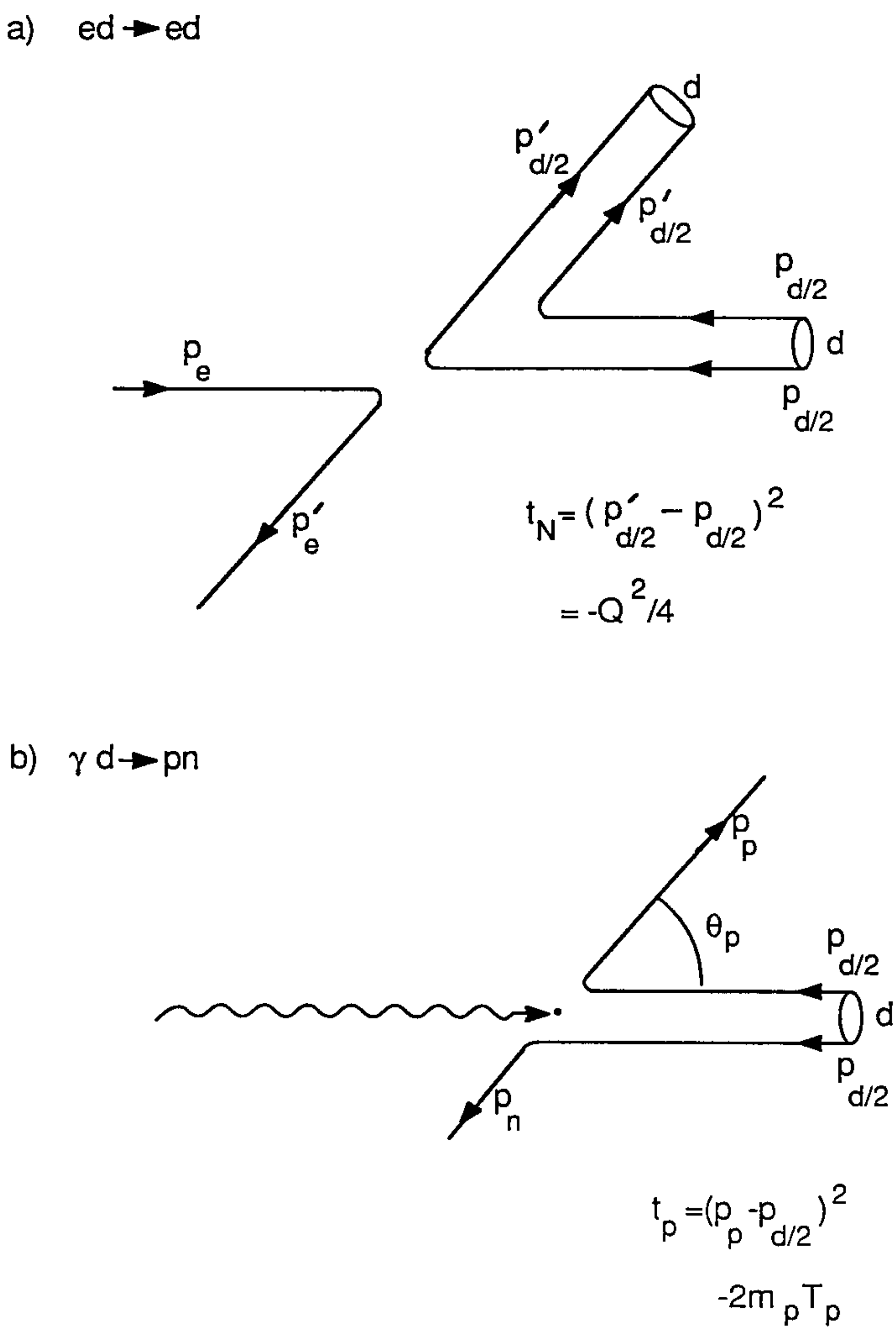


Fig. 2

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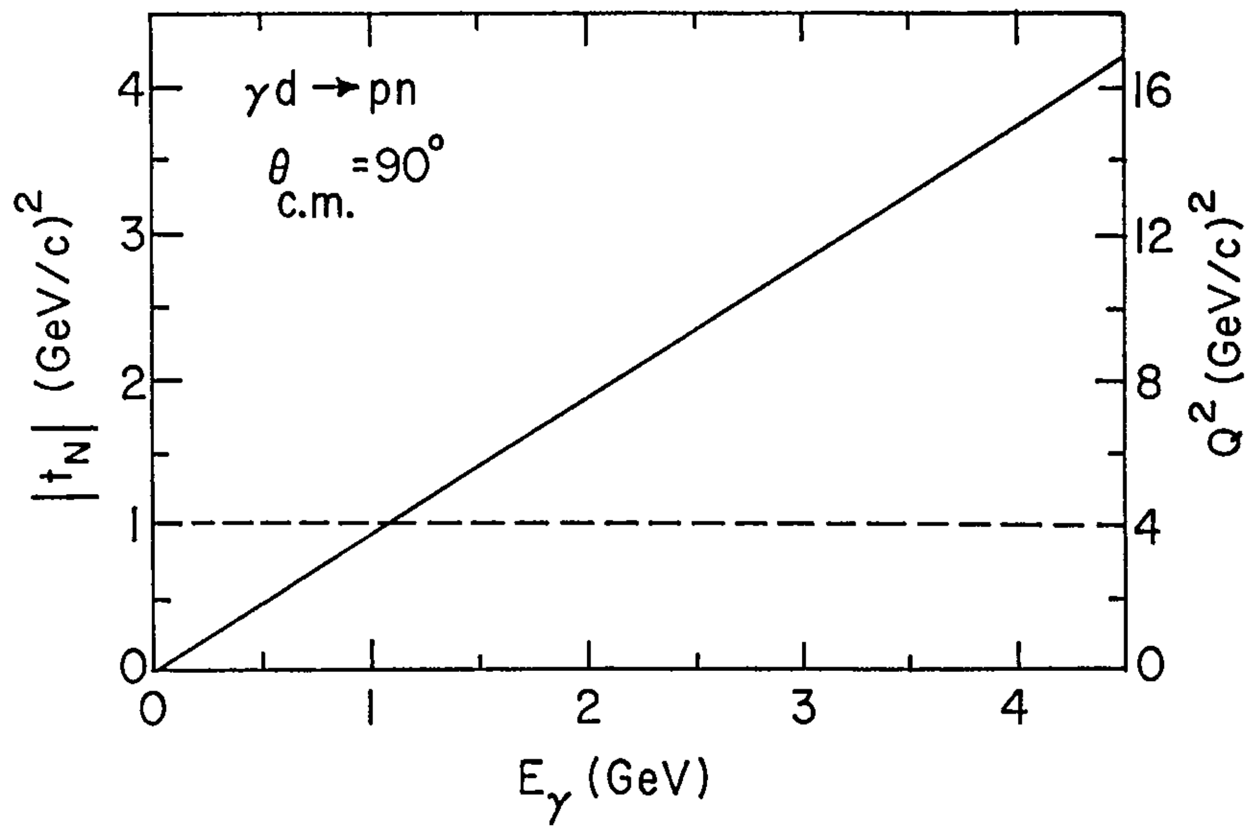
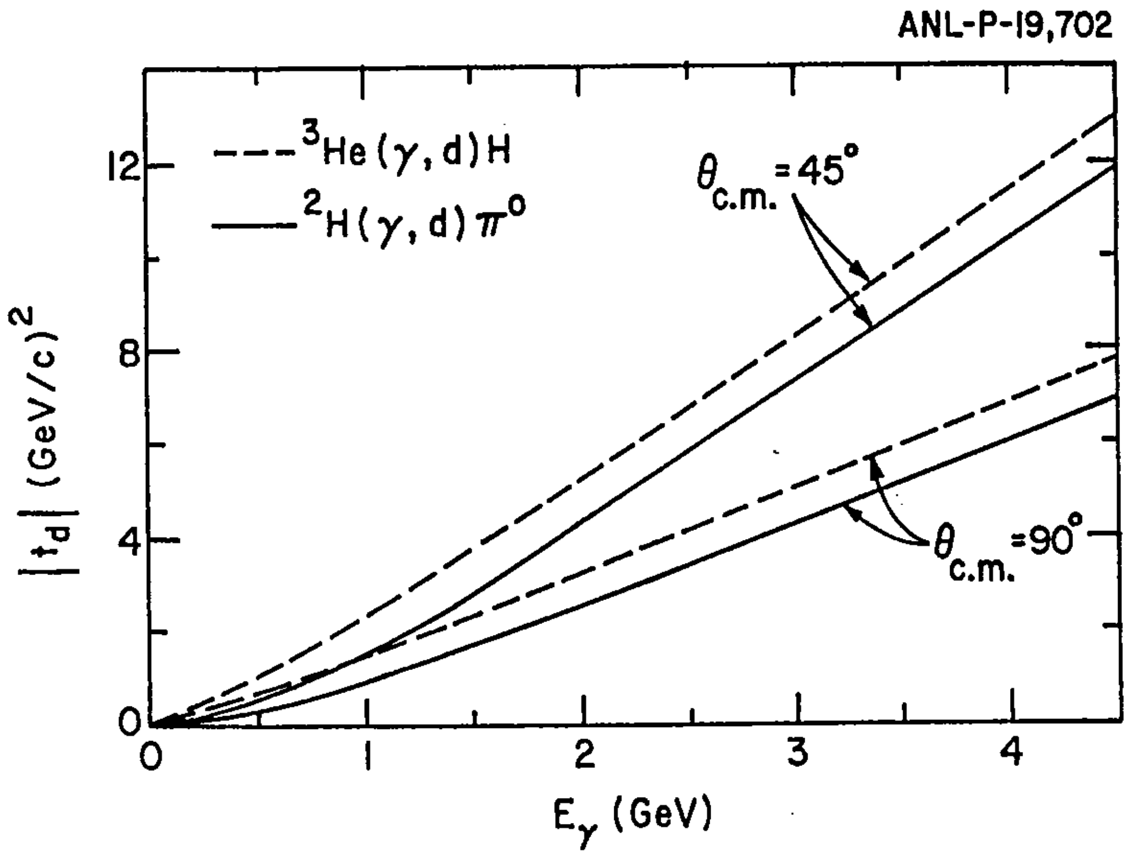


Fig. 3



ANL-P-19,702
$^3He(\gamma, d)H$
$^2H(\gamma, d)\pi^0$
$\theta_{c.m.} = 45°$
$\theta_{c.m.} = 90°$
$|t_d|$ $(GeV/c)^2$
E_γ (GeV)
0
4
8
12
0
1
2
3
4

Fig. 4

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Measurement of the Differential Cross Section for the Reaction $^2\mathrm{H}(\gamma,p)n$ at High Photon Energies and $\theta_{\mathrm{c.m.}}=90°$

J. Napolitano,[a] S. J. Freedman, D. F. Geesaman, R. Gilman, M. C. Green,[b] R. J. Holt, H. E. Jackson, R. Kowalczyk, C. Marchand,[c] J. Nelson, and B. Zeidman
Physics Division, Argonne National Laboratory, Argonne, Illinois 60439-4843

D. Beck, G. Boyd, D. Collins, B. W. Filippone, J. Jourdan, R. D. McKeown, R. Milner, D. Potterveld,[d] R. Walker, and C. Woodward
California Institute of Technology, Pasadena, California 91125

R. E. Segel and T.-Y. Tung
Northwestern University, Evanston, Illinois 60201

P. E. Bosted
American University, Washington, D.C. 20016

E. R. Kinney[c]
Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

Z.-E. Meziani
Stanford University, Stanford, California 94305

R. Minehart
University of Virginia, Charlottesville, Virginia 22901
(Received 8 June 1988)

We have measured the differential cross section for two-body deuteron photodisintegration at $\theta_{\mathrm{c.m.}}=90°$ and for photon energies between 0.8 and 1.6 GeV. At energies above $\simeq 1.2$ GeV, the data appear to obey a simple scaling law predicted by constituent-counting rules assuming parton degrees of freedom for the deuteron and nucleons. Agreement with model calculations based on meson exchange or "reduced nuclear amplitudes" is discussed.

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One of the most interesting and challenging issues to emerge in nuclear physics during the past decade concerns subnucleonic degrees of freedom. Pursuing this issue has led to attempts to describe nuclei in terms of the fundamental quark and gluon fields, rather than as collections of nucleons and mesons.[1] However, there is little experimental evidence to support these descriptions.

In this Letter, we present results of a measurement of the differential cross section for the reaction $^2\mathrm{H}(\gamma,p)n$ at $\theta_{\mathrm{c.m.}}=90°$ and photon energies between 0.8 and 1.6 GeV. This reaction has several features which suggest that it may serve as a testing ground for nucleon-meson versus quark/parton descriptions of the deuteron. First, it is an exclusive process which according to simple constituent-counting rules[2] should be described by $d\sigma/dt \propto 1/s^{11}$ for fixed $\theta_{\mathrm{c.m.}}$ and large enough values of s. [We use the standard definitions of s and t, namely that for the reaction $A+B\rightarrow C+D$, $s=(p_A+p_B)^2$ and $t=(p_A-p_C)^2$ where p_i is the four-momentum of particle i.] Second, a well-developed picture of this reaction in terms of nucleon and meson degrees of freedom exists and has been tested at lower energies.[3,4] Third, Brodsky and Hiller[5] have formulated a QCD-based description of this reaction in terms of "reduced nuclear amplitudes." (This approach has been successful in describing the elastic form factor of the deuteron[6] at energies well below the onset of constituent-counting behavior.) Our results strongly disagree with an existing meson-exchange calculation and suggest that, at the highest energies of our measurement, the cross section behaves according to the simple constituent-counting rule.

The experiment used the Nuclear Physics Injector at SLAC (NPAS) and facilities in end station A. Electrons were delivered in $\simeq 1.5$-μsec-long pulses with peak current up to $\simeq 20$ mA at a rate of $\simeq 90$/sec. The energy spread of the electron beam was defined using collimators which restricted the full width to $\simeq 0.25\%$. The integrated electron current was monitored by two toroids whose accuracy was better than 0.3%. We measured the beam energies to better than $\simeq 0.3\%$. The electron beam passed through removable 4% or 6% Cu radiators producing bremsstrahlung photons. Both electron and photon beams passed through the target before being absorbed in a water cooled beam dump.

Protons from the reaction ^{2}H$(\gamma,p)n$ corresponding to photon energies near the bremsstrahlung end point were momentum analyzed in the SLAC 1.6-GeV/c spectrometer[7] and detected in a multilayer system of plastic scintillator hodoscopes and drift chambers. An aerogel Cherenkov counter was used to help identify pion backgrounds. Five hodoscope layers, two segmented in the direction of momentum dispersion (X) and three in the direction of scattering angle (Y), triggered the apparatus and measured time of flight (TOF) over a $\simeq$3-m flight path. Three drift chambers were used, each having two planes in both the X and Y directions with $\simeq$1 cm wire spacing. Particles were tracked through the drift chambers allowing full reconstruction of momentum and trajectory. The overall rms momentum resolution obtained, including beam-energy spread, was $\simeq$0.3%. For the energies and angles studied, this was sufficient to separate protons due to the reaction ^{2}H$(\gamma,p)n$ from those due to reactions leading to additional final state particles. For each beam energy, one momentum setting was sufficient to cover the highest $\simeq$100 MeV of the bremsstrahlung spectrum as well as $\simeq$50 MeV above the end point. Measurements were made at a variety of center-of-mass angles. In this Letter we report results for $\theta_{\mathrm{c.m.}}=90°$ only.

Data were acquired through CAMAC electronics and read into a VAX-11/780 host computer through a PDP-11 "front-end" computer. The data-acquisition system was limited to one trigger per beam pulse so that all triggers were scaled and the extracted yields corrected. This correction was typically a few percent and 10% in the worst case. Dead-time corrections due to triggering electronics were negligible.

We used a 15-cm-long circulating liquid-deuterium (LD_2) target cell with 0.003-in. aluminum entrance and exit windows. A liquid-hydrogen (LH_2) target of identical dimensions was used for background subtraction. The transverse dimensions of the targets fully intercepted the electron and photon beams. The dominant background was from the reactions ^{27}Al$(\gamma,p)X$ and ^{27}Al$(\gamma,d)X$ on the target windows. We calculated the mass of each detected particle from its measured momentum and the velocity determined by the TOF system. This provided clear separation of protons from deuterons, and we confirmed that the deuteron background subtracted to zero using the LH_2 target. The pion and positron background rates were negligible for this analysis. The spectrometer was measured with use of elastic electron-proton scattering and checked by computer modeling. At present, the overall uncertainty in the absolute normalization is approximately $\pm$10%.

For each event, we determine the photon energy E_γ using the reconstructed momentum and scattering angle and assuming ^{2}H$(\gamma,p)n$ reaction kinematics. The resulting photon energy spectra are reduced by subtracting the LH_2 target yields from LD_2 target yields separately for runs with the "radiator in" and the "radiator out." Finally, the remaining radiator-out yield is subtracted fro the radiator-in yield. The resulting spectrum is assume to come from real photons produced in the external C radiator. The final yield spectra are shown in Fig. 1 f our lowest and highest beam energies at $\theta_{\mathrm{c.m.}}=90°$. It clear that the yield beyond the end point is consiste with zero, thereby providing additional evidence th backgrounds have been correctly subtracted.

Two cross-section values are determined from eac subtracted yield spectrum of the type shown in Fig. The yield below the end point is divided into two region excluding the highest 25 MeV and also excludin effective photon energies which allow yield from rea tions with additional particles in the final state, e.g ^{2}H$(\gamma,p)n\pi^0$. For each of these two regions, we averag the yield and determine the cross section from the targ thickness and density, our measured spectrometer accep tance, and the calculated bremsstrahlung yield[8] (correc ed for energy loss effects in the radiator[9]). The photo energy for each of the two regions is calculated with a average weighted by the bremsstrahlung yield. Th curves in Fig. 1 are determined by a linear interpolatio for the cross section, multiplying by the bremsstrahlun shape, and convoluting the product with a Gaussia response function with the expected photon energy res lution. The agreement is quite good over the enti range of photon energies supporting our simple metho of extracting cross sections over a small energy range.

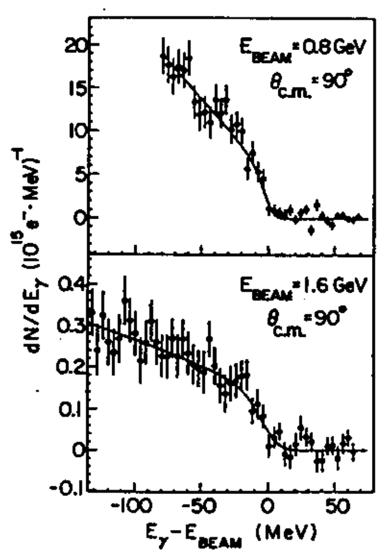

FIG. 1. Background-subtracted bremsstrahlung yiel dN/dE_γ as functions of reconstructed photon energy, for pr tons detected from the reaction ^{2}H$(\gamma,p)n$ at two differe beam energies. The yields are normalized by the number collected beam electrons. The solid curve is the product of t calculated bremsstrahlung yield and the measured cross secti folded with a Gaussian response function. The cross section assumed to be linear in energy over the range of each spe trum. The yields are consistent with zero beyond the e point.

Our results are presented in Fig. 2 where we plot the cross section after taking out certain "scaling" factors corresponding to simple constituent counting[2] [Fig. 2(a)] and to the reduced-nuclear-amplitudes approach[5] [Fig. 2(b)]. Evidence for either description then takes the form of the data becoming a (undetermined) constant above some photon energy. In each plot, we include the result of a recent calculation based on meson exchange,[4] scaled in the same fashion. Data from previous experiments[10] at lower energies are also included.

According to constituent-counting rules, the differential cross section for a particular exclusive process at fixed center-of-mass angle should approach the form $d\sigma/dt \propto 1/s^{n-2}$ where n is the total number of elementary fields. Consequently, for the reaction $^2\mathrm{H}(\gamma,p)n$ we might expect the quantity $s^{11}\,d\sigma/dt$, plotted in Fig. 2(a), to approach a constant above some energy.

The approach taken by Brodsky and Hiller[5] using the reduced nuclear amplitudes implies that the differential cross section should be given by the expression

$$\frac{d\sigma}{d\Omega_{\mathrm{c.m.}}}=\frac{1}{[s(s-M_d^2)]^{1/2}}F_p^2(\hat{t}_p)F_n^2(\hat{t}_n)\frac{1}{p_T^2}f^2(\theta_{\mathrm{c.m.}}),$$

where

$$\hat{t}_i=(p_i-\tfrac{1}{2}p_d)^2.$$

The nucleon elastic form factors are approximated by $F_N(t)=1/[1-t/(0.71\ \mathrm{GeV}^2)]^2$ and p_T is the nucleon transverse momentum. Accordingly, we plot the quantity $f^2(\theta_{\mathrm{c.m.}}=90°)$ in Fig. 2(b) as a function of photon energy. We note that while $f^2(\theta_{\mathrm{c.m.}})=\mathrm{const}$ is equivalent to satisfying simple constituent counting for higher photon energies, the ratio of their respective energy-dependent scaling factors changes by roughly a factor of 2 between 1.0 and 1.6 GeV. In principle, we might expect the use of reduced nuclear amplitudes to describe the data better at lower energies than by using simple constituent counting. Indeed, this appears to be true in the case of the deuteron elastic form factor.[6]

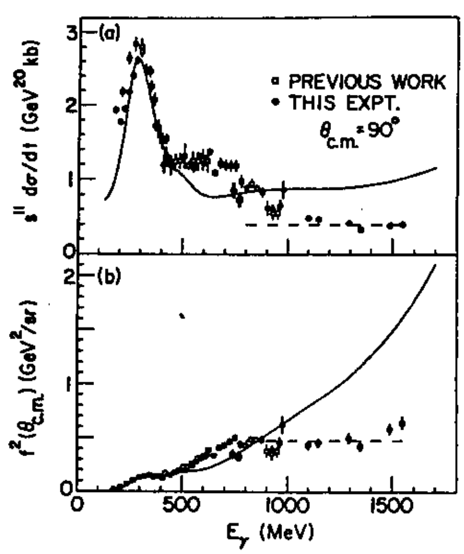

FIG. 2. Results of our experiment at $\theta_{\mathrm{c.m.}}=90°$ along with results of previous experiments at lower energies. The data are plotted so as to elucidate "scaling" as determined by (a) simple constituent counting (Ref. 2) and by (b) a formalism based on the reduced nuclear amplitudes (Ref. 5). The solid lines are the result of a recent calculation based on meson exchange (Ref. 4). The dashed lines represent constants that approximate the data at high energy but whose magnitudes are not predicted by any model. Only statistical errors and errors due to the uncertainty in the end-point energy are shown.

It is immediately clear from Fig. 2 that the meson-exchange calculation of Ref. 4 does not describe the data above $E_\gamma=500$ MeV. It does not appear that agreement with our data can be achieved by adjusting the various parameters in the calculation, although this is not surprising since the calculation does not incorporate all possible degrees of freedom.[4] Indeed, fully relativistic calculations which exploit the range of assumptions about, for example, deuteron wave functions and the specific nature of the exchange currents, as well as including all relevant degrees of freedom, must be done before definite statements can be made about agreement with an entire class of such models. We note that such calculations are largely constrained by data from other reactions.

Despite the very low energy ($s\simeq 2M_d^2$), our data seem to be described by the simple constituent-counting relation for $E_\gamma \geq 1.2$ GeV,[2] although the data do not extend to high enough energy to identify logarithmic or otherwise slowly varying deviations as suggested from QCD. We note that a fit to the data above 1.2 GeV with the form $d\sigma/dt=A/s^n$ yields $n=10.5\pm0.7$. The data are reasonably described by the formalism of Brodsky and Hiller,[5] although it deviates somewhat at the highest photon energies. Higher-energy data are needed to distinguish conclusively between the two "quark/parton" descriptions and to determine whether or not the s^{-11} dependence persists over a larger range in energy.

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[a]Present address: Physics Division, Continuous Electron Beam Accelerator Facility, Newport News, VA 23606.

[b]Present address: LeCroy Research Systems, Spring Val-